MEMS DEVICE HAVING AN ACTUATOR WITH CURVED ELECTRODES

AN APPLICATION FOR

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Description

MEMS DEVICE HAVING AN ACTUATOR WITH CURVED ELECTRODES

Cross-Reference to Related Application

This nonprovisional application claims the benefit of U.S. Provisional Application No. 60/256,683, filed December 19, 2000, U.S. Provisional Application No. 60/256,604, filed December 19, 2000, U.S. Provisional Application No. 60/256,607, filed December 19, 2000, U.S. Provisional Application No. 60/256,610, filed December 19, 2000, U.S. Provisional Application No. 60/256,611, filed December 19, 2000, U.S. Provisional Application No. 60/256,674, filed December 20, 2000, U.S. Provisional Application No. 60/256,688, filed December 19, 2000, U.S. Provisional Application No. 60/256,689, filed December 19, 2000, and U.S. Provisional Application No. 60/260,558, filed January 9, 2001, the disclosures of which are incorporated by reference herein in their entirety.

Technical Field

The present invention relates to micro-electro-mechanical systems (MEMS) devices having actuators. More particularly, the present invention relates to optical MEMS devices having actuators that employ electrostatic energy mechanisms for moving an actuating device linearly.

Background Art

In communication networks, optical transmission systems are often used for the transmission of data signals between network terminals such as

telephones or computers. Optical transmission systems transmit data signals via data-encoded light through fiber optics. Many functions in optical switching systems require the movement of an actuating device in order to interact with the light output from "incoming" fiber optics. Among the functions requiring light interaction are redirecting light from one fiber optic to another, shuttering light, filtering light, and converting light output to electrical form.

In order to perform optical switching system functions, small machines, known as micro-electro-mechanical systems (MEMS) devices, are typically used to interact with transmitted light. MEMS is a technology that exploits lithographic mass fabrication techniques of the kind that are used by the semiconductor industry in the manufacture of silicon integrated circuits. Generally, the technology involves shaping a multilayer structure by sequentially depositing and shaping layers of a multilayer wafer that typically includes a plurality of polysilicon layers that are separated by layers of silicon oxide and silicon nitride. Typically, individual layers are shaped by a process known as etching. The etching process is generally controlled by masks that are patterned by photolithographic techniques. MEMS technology can involve the etching of intermediate sacrificial layers of the wafer to release overlying layers for use as thin elements that can be easily deformed or moved to function as an actuator.

An actuating device is any MEMS device component that is movable with respect to a substrate on which the MEMS device is attached due to forces generated by the MEMS device. Oftentimes, MEMS devices in optical switching systems interact with light by moving an actuating device, such as a shutter, in and out of a light pathway for blocking, filtering or reflecting transmitted light. Some of the most common and widely used means employed by MEMS devices

for generating a force on an actuating device consist of electrostatic, thermal (including shape memory alloys), and magnetic energy mechanisms. Typically, MEMS devices employing thermal or magnetic energy mechanisms have higher power consumption for generating the same forces as those employing electrostatic energy mechanisms.

Electrostatic actuation operates on the principle of Coulomb's law that two conductors with equal and opposite charge will generate an attractive force between them. Electrostatic actuation is generally implemented by applying a voltage potential between a fixed and movable electrode. This difference in voltage potential generates an equal and opposite charge on the fixed and movable electrode which causes movement of the movable electrode towards the fixed electrode.

MEMS devices employing electrostatic actuation move actuating devices in a curvilinear or linear direction depending on the type of MEMS device. In most applications, an array of MEMS devices employing linear motion can be more densely packaged on a substrate than MEMS devices employing curvilinear motion. However, MEMS devices employing linear motion typically have greater power requirements than those MEMS devices employing curvilinear motion. Furthermore, actuating device displacement ranges are typically lower for MEMS device employing linear motion.

Therefore, it is desirable to improve the packaging density of optical MEMS devices fabricated on a substrate by providing linear motion to a MEMS device employing linear motion. It is also desirable to provide a MEMS device having low power requirements. Furthermore, it is desirable to provide a MEMS device having high actuating device displacement ranges.

Disclosure of the Invention

According to one aspect of the present invention, an actuator is provided that includes a substrate having a substantially planar surface and an actuating device movable in a substantially linear direction relative to the substrate. The actuator includes at least one bendable electrode beam attached to the actuating device and having an end attached to the substrate. The electrode beam is flexible between the actuating device and the end of the electrode beam attached to the substrate. Furthermore, the actuator includes at least one electrode attached to the substrate. The electrode has a curved surface aligned in a position adjacent the length of the electrode beam, whereby the actuating device is movable in its substantially linear direction as the electrode beam moves in a curved fashion corresponding substantially to the curved surface of the electrode.

According to a second aspect of the present invention, a method is provided for moving an actuating device in a linear direction. The method includes providing a substrate having a substantially planar surface and providing an actuating device movable in a substantially linear direction relative to the substrate. The method also includes providing at least one bendable beam attached to the actuating device and having an end attached to the substrate. The electrode beam is flexible between the actuating device and the end of the electrode beam attached to the substrate. Furthermore, the method includes providing at least one electrode attached to the substrate. The electrode has a curved surface aligned in a position adjacent the length of the electrode beam. Additionally, the method includes applying a voltage across the electrode beam and curved electrode to move the electrode beam in a curved

fashion corresponding to the curved surface of the electrode, whereby the actuating device moves in a substantially linear direction.

Accordingly, it is an object of the present invention to provide an actuator to provide linear motion to an actuating device.

It is another object of the present invention to provide an actuator having low power requirements.

Some of the objects of the invention having been stated hereinabove and which are achieved in whole or in part by the present invention, other objects will become evident as the description proceeds when taken in connection with the accompanying drawings as best described hereinbelow.

Brief Description of the Drawings

Exemplary embodiments of the invention will now be explained with reference to the accompanying drawings, of which:

Figure 1 is a schematic view of an electrostatic comb-drive type MEMS device for providing motion to an actuating device in a linear direction parallel to the plane of a substrate surface;

Figure 2 is a schematic view of an electrostatic, curved electrode actuator type MEMS device for moving an actuating device in a curved direction parallel to the plane of a substrate surface;

Figure 3 is a schematic view of an optical MEMS device having an actuating device for linear motion according to an embodiment of the present invention;

Figure 4 is a schematic view of an optical MEMS device in an active state in which a shutter is positioned outside of a light pathway;

Figure 5 is a schematic view of a two-fold flexure attached to an electrode beam and a frame;

Figure 6 is a schematic view of a one-fold flexure for attaching an electrode beam to a frame;

Figure 7 is a schematic view of a crab leg flexure for attaching an electrode beam to a frame;

Figure 8 is a diagram illustrating an actuator model for use in computer-aided design (CAD) electro-mechanical simulations of movement of an electrode beam in accordance with an embodiment of the present invention;

Figure 9 is a diagram illustrating CAD simulation results as a function of curved surface gap distance and voltage for a one-fold flexure design;

Figure 10 is a diagram illustrating CAD simulation results as a function of curved surface gap distance and voltage for a two-fold flexure design;

Figure 11 a schematic view of a bi-directional actuator for an optical MEMS device according to another embodiment of the present invention;

Figure 12 a schematic view of an optical MEMS device having a shutter attached to two actuator pairs according to another embodiment of the present invention;

Figure 13 a schematic view of a two-stage mode actuator for an optical MEMS device according to an embodiment of the present invention;

Figure 14 a schematic view of a two-stage mode actuator positioned at the end of the first stage of actuation;

Figure 15 a schematic view of a two-stage mode actuator positioned at the end of the second stage of actuation;

Figure 16 a schematic view of another embodiment of a MEMS device for moving a shutter in accordance with the present invention;

Figure 17 a schematic view of a set of light pathways extending perpendicular to a substrate and a set of bi-directional actuators;

Figure 18 a schematic view of another set of light pathways extending perpendicular to a substrate and a set of uni-directional, two-stage actuators; and

Figure 19 a schematic view of another set of light pathways and a set of frame, bi-directional actuators.

Detailed Description of the Invention

The present invention has many advantages apparent to those of skill in the art over known type MEMS devices employing electrostatic actuation. One known type MEMS device employing electrostatic actuation for providing linear motion is an electrostatic comb-drive type MEMS device. Referring to FIG. 1, a schematic view of an electrostatic comb-drive type MEMS device **100** is illustrated for providing motion to an actuating device **102** in a linear direction (indicated by direction arrows **104**) parallel to the plane of substrate surface **106**. Linear motion is provided by applying a voltage across fixed combs generally designated **108**. This generates a force on a movable arm **110**, thereby moving actuating device **102**. Movable arm **110** is attached to substrate surface **106** via a spring **112** and an anchor **114**. Spring **112** allows movable arm **110** to have motion with respect to substrate surface **106**. As compared to MEMS device **100**, the present invention is typically able to produce larger forces and actuating device displacement for comparable applied voltages and size.

Another MEMS device employing electrostatic actuation known to those of skill in the art is a curved electrode type MEMS device. This MEMS device provides an actuating device with curvilinear motion. Referring to FIG. 2, a schematic view of an electrostatic, curved electrode actuator type MEMS device **200** is illustrated for moving an actuating device **202** in a curved direction (indicated by direction arrows **204**) parallel to the plane of a substrate surface **206**. MEMS device **200** is attached to substrate surface **206**. MEMS device **200** includes a bendable electrode beam **208**, a curved electrode **210** attached to substrate surface **206**, and an anchor **212** attached to substrate surface **206**. On the application of a voltage across curved electrode **208** and electrode beam **210**, MEMS device **200** moves actuating device **202** in a curved direction towards curved electrode **210**. As stated above, MEMS devices employing curvilinear motion cannot be packaged as densely in an array as MEMS devices employing linear motion.

In accordance with one embodiment of the present invention, a MEMS device having actuators is provided for providing linear motion to an actuating device. Referring to FIG. 3, a schematic view of an optical MEMS device generally designated **300** having an actuating device, a shutter **302** in this example, for linear motion according to an embodiment of the present invention is provided. MEMS device **300** and shutter **302** are fabricated onto a substrate surface **304** and attached together via a frame **306** of shutter **302**. MEMS device **300** includes electrodes **308** and **310**, electrode beams **312** and **314**, and anchors **316** and **318**. Frame **306** is attached to substrate surface **304** via a flexible portion **322** and **324**, electrode beams **312** and **314**, and anchors **316** and **318**.

Shutter **302** and frame **306**, combined, form an actuating device which is provided relative movement with respect to substrate surface **304** in a linear direction **x 320** on the application of a voltage across electrode beams **312** and **314** and electrodes **308** and **310**, respectively. In this embodiment, shutter **302** functions to interact with light. In an alternate embodiment, another suitable actuating device known to those of skill in the art can be attached to electrode beams **312** and **314** for providing movement in a linear direction. For example, the MEMS device of the present invention can have an actuating device adapted for use as a DC microswitch/microrelay, an RF microswitch, a fluidic switch, a variable optical attenuator, an infrared detector, a electromechanical latch actuator, an actuator to drive the push pawl and drive pawl in stepper motor applications, a linear stepper motor, a driver in a linear impact motor, a linear actuator in a microimpact tester, a linear actuator to drive pop up mirrors, gratings, various other micro-components, components requiring out-of-plane movement, a self testable accelerometer, a variable capacitor, and other such micro-components requiring motion.

Voltage can be provided by any suitable voltage source for providing a voltage across electrode beams **312** and **314** and electrodes **308** and **310**, respectively, as described below. As shown in FIG. 3, MEMS device **300** is in its inactive state and position, wherein no voltage is applied across electrode beams **312** and **314** and electrodes **308** and **310**, respectively.

MEMS device **300** is uni-directional, meaning motion is provided in only one direction from its position in an inactive state (as shown). Shutter **302** and frame **306** move in a direction **x 320** in a plane (the plane formed by direction arrows **x 320** and **y 326**) parallel to substrate surface **304**. Motion is provided on

the application of a voltage across electrode beams **312** and **314** and electrodes **308** and **310**, respectively, which thereby produces an attractive force between electrode beams **312** and **314** and electrodes **308** and **310**, respectively. At a threshold voltage the attractive force is great enough to pull in each electrode beam **312** and **314** adjacent its corresponding electrode **308** and **310**, respectively. Similarly, on the removal of a voltage across electrode beams **312** and **314** and its corresponding electrode **308** and **310**, respectively, shutter **302** and frame **306** will move in a direction opposite direction **x 320**.

In another embodiment, the analytic function describing the shape of surfaces **330** and **332** of electrodes **308** and **310**, respectively, can be modified to produce a continuous monotonic motion of shutter **302** and frame **306**. The motion begins with an abrupt motion and then the motion is continuous as beams **312** and **314** increasingly establish greater contact with surfaces **330** and **332** of electrodes **308** and **310**, respectively. With these two embodiments, two different motions can be established with the present patent. The first motion has two stable states: "Open"/"Closed", "On"/"Off", "Unobstructed"/"Obstructed". The second motion has many stable states that define the continuous motion of shutter **302** and allow variable attenuations of a light signal.

In this embodiment, light is transmitted along a light pathway **328** (shown as broken lines) perpendicular to substrate surface **304**. In operation, shutter **302** can be moved from a position intercepting light pathway **328** (as shown) to a position outside light pathway **328**. Referring to FIG. 4, a schematic view of an optical MEMS device **300** is illustrated in an active state in which shutter **302** is positioned outside of light pathway **328**. In the active state, voltage has been applied across electrode beams **312** and **314** and its corresponding electrode

308 and **310**, respectively, causing frame **306** to move in a linear direction **x 320**. When the applied voltage is removed or reduced sufficiently, the elastic restoring force of electrode beams **312** and **314** returns them to a shape and position as shown in FIG. 3.

Shutter **302** in this embodiment is preferably made of a material that does not transmit light. Non-limiting examples of optically non-transmissible materials include silicon with a gold (Au) or Aluminum (Al) film or other suitable materials known to those of skill in the art. Alternatively, shutter **302** can be made of a transmissible material including the non-limiting examples glass, quartz, and sapphire. In each case, the transmissibility is determined by the material and the wavelength of light.

Substrate surface **304** is composed of an electrically insulated material such as Gallium Arsenic (GaAs) substrate, a glass substrate, an oxidized silicon wafer or a printed circuit board (PCB). In this embodiment, the substrate is transmissible to light, thus, allowing for light transmission along light pathway **328** through the substrate. The transmissibility can be associated with the material and the wavelength of the incident light or it can be associated with an optical aperture through substrate **304**. In the case of the transmissible material, the transmission efficiency can be improved be the addition of an antireflective coating on surface **304**.

Electrode beams **312** and **314** are each connected at one end to anchors **316** and **318**, respectively. At a distal end, electrode beams **312** and **314** are connected to frame **306**. Flexible portions **322** and **324** represent the natural flexibility of electrode beams **312** and **314**, respectively. This flexibility serves to translate the curvilinear motion of the ends of electrode beams **312** and **314**

connected to frame **306** into a linear motion. In some instances, electrode beams **312** and **314** can buckle due to excessive residual stress due to the fabrication process, temperature, or other stressors. Therefore, in an alternate embodiment, flexures can be included with electrode beams **312** and **314** to relieve residual stress and prevent buckling.

Flexures can be integrated with an electrode beam at one end for attachment to a frame. In alternative embodiments of the present invention, a flexure can be a compliant hinge, compliant joint, spring, coil spring, or any other suitable flexure known to those of skill in the art. Referring now to FIG. 5, a schematic view of a two-fold flexure **500** attached to an electrode beam **502** and a frame **504** is illustrated. In one embodiment, two-fold flexure generally designated **500** is manufactured of the same piece of material as electrode beam **502**. Alternatively, flexure can be made of a different piece of material. The piece of material is formed into a shape having a fold **506** in one direction **x 508** and another fold **510** in a direction opposite direction **x 508**. Folds **506** and **510** serve as a pivot conducive for translating movement of the electrode beam **502** into direction **x 508**. Furthermore, flexure **500** can translate movement of electrode beam **502** into a direction opposite direction **x 508**.

In another embodiment, a one-fold flexure can be used for attaching an electrode beam to a frame. Referring now to FIG. 6, a schematic view of a one-fold flexure generally designated **600** for attaching an electrode beam **602** to a frame **604** is illustrated. In one embodiment, one-fold flexure **600** is manufactured of the same piece of material as electrode beam **602**. The piece of material is formed into a shape having a fold **606** in direction **x 608**. Fold **606**

serves as a pivot conducive for movement of frame **604** in direction **x 608** at the point of attachment of electrode beam **602** and frame **604**.

In yet another embodiment, a crab leg flexure can be used for connecting electrode beams **312** and **314** to frame **306** (as shown in FIGs. 3 and 4). Referring now to FIG. 7, a schematic view of a crab leg flexure generally designated **700** for attaching an electrode beam **702** to a frame **704** is illustrated. In one embodiment, crab leg flexure **700** is manufactured of the same piece of material as electrode beam **702**. The piece of material is formed into a shape having a half fold **706** in direction **x 708**. Frame **704** is attached at half fold **706**. Half fold **706** serves as a pivot conducive for movement of frame **704** in direction **x 708** at the point of attachment of electrode beam **702** and frame **704**.

Referring again to FIG. 3, as mentioned above actuator **300** is shown in an inactive state because voltage is not applied across either electrode beam **312** and electrode **308** or electrode beam **314** and electrode **310**. Therefore, electrode beams **312** and **314** are shaped in their natural position, a substantially straight line, because they are not attracted to either electrodes **308** and **310**. As a result, electrode beams **312** and **314** are not bent towards either electrode **308** or electrode **310**.

Electrodes **308** and **310** are positioned in a direction **x 320** with respect to electrode beams **312** and **314** for attracting electrode beams **312** and **314** in direction **x 320** on the application of voltage. Electrodes **308** and **310** have convex, curved surfaces **330** and **332** adjacent to and facing electrode beams **312** and **314**. Curved surfaces **330** and **332** each extend a distance **a 334** in direction **x 320**.

Each electrode beam **312** and **314** extends a length from a first end (connected to anchors **316** and **318**, respectively) to a second end connected by flexible portions **322** and **324**, respectively, to frame **306**. In this embodiment, each electrode beam **312** and **314** has a bendable portion extending substantially the entire length from the first end to the second end. Alternatively, the bendable portion can only extend a portion of the length of electrode beam or several different portions.

As shown, each electrode beam **312** and **314** is closest to curved surfaces **330** and **332**, respectively, at a point on its length furthest from frame **306**. When a voltage is applied across electrodes **312** and **314** and electrode beams **312** and **314**, respectively, this point furthest from frame **306** is where the attractive force is greatest. On the application of a threshold voltage, electrode beams **312** and **314** will begin to bend at this point in a direction **x 320** towards curved surfaces **330** and **332**, respectively. Electrode beams **312** and **314** bend due the attractive force pulling them towards electrodes **312** and **314**, respectively, and due to the attachment of electrode beams **312** and **314** to anchors **316** and **318**, respectively.

As points of electrode beams **312** and **314** closest to curved surface **330** and **332** move closer to curved surfaces **330** and **332**, respectively, adjacent points in a direction closer to frame **306** begin to move closer to curved surfaces **330** and **332**. At a close enough distance to curved surface **330** and **332**, a point along the length of each electrode beam **312** and **314** will be attracted with great enough force to bend electrode beam further in direction **x 320**. As electrode beams **312** and **314** bend closer to curved surface **312** and **314**, they each form into a shape similar to the contour of curved surfaces **330** and **332**. Eventually,

the second end of each electrode beam **312** and **314**, connected to frame **306**, is displaced approximately distance **a 334** to a position adjacent curved surfaces **330** and **332**, respectively. This movement of electrode beams **312** and **314** serves to displace frame **306** in direction **x 320** with respect to substrate surface **304**.

Computer-aided design (CAD) tools can be used for runnning electro-mechanical simulations of the present invention. Referring to FIG. 8, a diagram of an actuator model generally designated **800** for use in CAD electro-mechanical simulations of the movement of electrode beam **802** is illustrated in accordance with an embodiment of the present invention. An electrode **804** having a curved surface **806** and electrode beam **802** having an end **808** for attachment to a frame **810** is shown. This simulation characterizes electrode end **808** displacement in a direction **x 812** as a function of the distance **d1 814** that curved surface **806** extends in a direction **x 812**. Furthermore, displacement is characterized as a function of voltage across electrode **804** and electrode beam **802** and flexure type for attachment of end **808** to a frame (not shown). The distance of displacement of end **808** to a point of maximum displacement **814**, shown by the electrode beam (shown as a broken line at reference numeral **816**) in a position of maximum displacement, is a distance **d2 818**. Electrode beam **806** is attached to an anchor **824** at an end distal from end **808**. Boundary conditions for the simulations included fixing all six degrees of freedom at anchor **824** and fixing end **808** to translate in direction **x 812** and fixing the slope of end **808** to be zero in the plane of directions **x 812** and **y 822**. Electrode beam **802** is set to zero volts and the voltage of electrode **804** was varied to generate an electrostatic attractive force between electrode beam **806** and electrode **804**.

Displacement of the end of electrode beam **802** a distance **d2 818** versus applied voltage across electrode **804** and electrode beam **802** is defined by a region in which displacement is not constrained by curved surface **806** and a region in which displacement is constrained by curved surface **806**. Stable or unstable displacement versus voltage characteristics can be achieved in each region through various design parameters. Stable actuator performance is defined by continuous displacement versus voltage curves. Unstable actuator performance is defined by displacement versus voltage curves with discontinuous steps. Unstable actuator performance typically occurs when electrostatic force on electrode beam **802** is greater than the elastic restoring force of the deformed electrode beam **802**. Generally, the greatest displacement for a given voltage can be achieved with actuators exhibiting unstable behavior.

Frame displacement versus applied voltage performance characteristics depend upon the design of the electrode beams, the design of the flexures, the curved surface of electrodes, and the initial gap distance between the electrode beam and electrode. Electrode beam compliancy is defined by the beam's cross-section, length, and material properties. The flexure spring constant is a function of the flexure cross-section, material properties, and its shape. The flexures relieve thermal and residual material stresses, and accommodate bending moments produced at the end of the beam during the active state.

The shape of an electrode's curved surface can assume many different forms. For example, the shape of a curved surface can be described by the following equation normalized to the distance the maximum distance separating the curved surface and the electrode beam (wherein $d1$ represents the maximum distance separating the electrode beam and the curved surface, x

represents the position along an axis parallel to electrode beam, L represents the length of the electrode in a direction parallel to the electrode beam, and n represents the exponential order of the curve with $n \geq 0$):

$$S(x) = d1 * \left(\frac{x}{L}\right)^{n}$$

For $n \leq 2$, the actuator tends to exhibit unstable displacement versus voltage characteristics in that once the beam is first pulled-in to the electrode it will deform along the entire electrode length with the proper compliant flexure design. For $n \geq 2$, the actuator tends to exhibit stable continuous displacement versus voltage characteristics once the beam is first pulled-in to the fixed electrode.

Various electrode beam and electrode dimensions were used in the CAD simulations for the design of FIG.8. Boundary conditions for the simulations included fixing all six degrees of freedom at anchor **824** and applying a symmetry boundary condition fixing the end **808** to translate linearly in a direction **x 812**. Electrode beam **802** potential voltage was set to zero volts and the electrode **804** voltage was varied to generate an electrostatic attractive force between electrode beam **802** and electrode **804**.

Typical electrode beam dimensions and material properties used in the simulations are as follows: length (450 micrometers)(distance **d3 820**); beam thickness in direction of bending (i.e., direction **x 812**) (2.0 micrometers); beam width (direction perpendicular to direction **x 812** and direction **y 822**)(3.5 micrometers); and the Young's modulus of polysilicon described by E_{poly} the Young's modulus of polysilicon described by (165 Gpa).

Typical dimensions of curved surface **806** of electrode **804** were as follows: length (440 micrometers)(distance **d4 824**) and maximum distance (distance **d1 810**)(between about 35 – 50 micrometers). Furthermore, a dielectric material having a thickness of 0.5 micrometers is placed on curved surface **804** to prevent shunting between electrode **802** and electrode beam **806**.

Referring to FIG. 9, a diagram illustrating CAD simulation results as a function of curved surface gap distance (distance **d1 814**) and voltage for a one-fold flexure design is provided. The diagram shows graphs for displacement **d1 814** for 35, 40, 45, 50, 55, and 60 micrometers. Broken lines show the unstable pull-in regions. For example, a one-fold flexure with a displacement d1 of 35 micrometers has a pull-in voltage of approximately 56 volts and end displacement of 27.7 micrometers for an applied voltage of 80 volts. A crab leg flexure simulation with the same configuration as above produced pull-in voltage of approximately 60 volts with less end displacement, 26.2 micrometers.

Referring to FIG. 10, a diagram illustrating CAD simulation results as a function of curved surface gap distance **d1 814** and voltage for a two-fold flexure design is provided. The diagram shows graphs for displacement d1 for 40, 50, and 60 micrometers. Broken lines show the unstable pull regions. Two-fold flexures produced the best simulation results. For example, a two-fold flexure with a curved surface gap distance **d1 814** of 60 micrometers produced an end displacement of 63 micrometers for an applied voltage of 100 volts. For comparison, a one-fold flexure with the same configuration produced an end displacement of approximately 35 micrometers for an applied voltage of 100 volts.

Movement of a frame from an inactive position in two directions can be achieved by placement of electrodes on opposite sides of an electrode beam. Referring to FIG. 11, a schematic view of a bi-directional actuator generally designated **1100** for an optical MEMS device according to another embodiment of the present invention is illustrated. Actuator **1100** includes an electrode beam **1102** and electrodes **1104** and **1106**, each adjacent electrode beam **1102**. On the application of a voltage between electrode **1104** and electrode beam **1102**, electrode beam **1102** moves towards electrode **1104** causing attached frame **1110** to move in a direction **x 1108**. Conversely, on the application of a voltage between electrode **1106** and electrode beam **1102**, electrode beam **1102** moves towards electrode **1106** causing attached frame **1110** to move in a direction opposite direction **x 1108**. As shown in this example, a two-fold flexure **1112** is used to attach electrode beam **1102** to frame **1110**. Alternatively, any other type of flexure described above can be used.

A bi-directional actuator as described above can be used along with other actuators for moving an actuating device bi-directionally. Referring to FIG. 12, a schematic view of an optical MEMS device generally designated **1200** having a shutter **1202** attached to two actuator pairs according to another embodiment of the present invention is illustrated. One actuator pair consists of electrode beams **1204** and **1206**, electrodes **1208** and **1210** for movement in a direction **x 1212**, and electrodes **1214** and **1216** for movement in a direction opposite direction **x 1212**. Another actuator pair consists of electrode beams **1218** and **1220**, electrodes **1222** and **1224** for movement in direction **x 1212**, and electrodes **1226** and **1228** for movement in a direction opposite direction **x 1212**. Actuator pairs function to move frame **1230** and shutter from a position in an

inactive state to positions in a direction **x 1212** and opposite direction **x 1212**. Electrode beams **1204**, **1206**, **1218**, and **1220** are attached via two-fold flexures **1230**, **1232**, **1234**, and **1236**, respectively. Alternatively, any type of flexure or attachment described above can be used.

In this embodiment, shunting between electrodes beams **1204**, **1206**, **1218**, and **1220** and electrodes **1208**, **1210**, **1214**, **1216**, **1222**, **1224**, **1226**, and **1228** is prevented by a sets of bumpers lined along curved surfaces **1238**, **1240**, **1242**, **1244**, **1246**, **1248**, **1250**, and **1252**. For example, bumpers **1254**, **1256**, **1258**, **1260**, **1262**, **1264**, **1266**, and **1268** are positioned along curved surface **1238** between curved surface **1238** and electrode beam **1208**. On the application of a voltage, electrode beam **1204** is stopped from further movement towards curved surface **1238**. Bumpers **1254**, **1256**, **1258**, **1260**, **1262**, **1264**, **1266**, and **1268** are made of a dielectric and can be made of any suitable non-conductive material. In another embodiment, bumpers **1254**, **1256**, **1258**, **1260**, **1262**, **1264**, **1266**, and **1268** can be made of a conductive material that is electrically isolated from the electrodes beams **1204**, **1206**, **1218**, and **1220** and electrodes **1208**, **1210**, **1214**, **1216**, **1222**, **1224**, **1226**, and **1228**

Large frame displacement in one direction can be achieved by employing a two-stage actuation design. Referring to FIG. 13, a schematic view of a two-stage mode actuator generally designated **1300** for an optical MEMS device according to another embodiment of the present invention is illustrated. Actuator **1300** includes an electrode beam **1302** corresponding to electrode **1304** and electrode beam **1306** corresponding to electrode **1308**. The movement of a frame **1310** is limited to a linear direction parallel to direction **x 1312**. Electrodes **1304** and **1308** are separated in a direction **x 1312** by a distance **d1 1314**.

Electrode beam **1302** is attached to electrode beam **1306** via an extension arm **1316**, which extends in direction **x 1312** approximately a distance **d2 1318**. Electrode beam **1302** is attached to substrate surface **1320** via anchor **1322**. Electrode beam **1306** is attached to frame **1310** via two-fold flexure **1324**. Alternatively, any type of above described flexure can be used.

As shown in FIG. 13, actuator **1300** is in the inactive state having no voltage applied. On the application of a voltage across electrode beam **1302** and electrode **1304**, actuator **1300** enters the first stage. Referring to FIG. 14, a schematic view of an actuator **1300** is illustrated positioned at the end of the first stage of the two-stage mode of actuation. Actuator **1300** enters the first stage when a sufficient voltage is applied across electrode beam **1302** and electrode **1304**. As described above, an attractive force results and electrode beam **1302** is bent along the contour of curved surface **1400**. As shown, due to the displacement of extension arm **1316** in a direction **x 1312**, electrode beam **1306** and frame **1310** are moved a distance **d3 1402** that curved surface **1400** extends in direction **x 1312**. Because electrode beam **1306** is moved in a direction **x 1312** to a position closer to electrode **1308**, a smaller voltage applied across electrode beam **1306** and electrode **1308** to move electrode beam **1306**.

The movement of electrode beam **1306** to curved surface **1404** of electrode **1308** begins the second stage of actuation. Referring now to FIG. 15, a schematic view of actuator **1300** is illustrated positioned at the end of the second stage of actuation. Actuator **1300** enters the second stage at the end of the first stage, after electrode beam **1302** has bent along the contour of curved surface **1400**. At this point, electrode beam **1306** is positioned close enough to electrode **1308** such that an applied voltage between them bend electrode beam

1306 along the contour of curved surface **1404**. As a result of the second stage of actuation, frame **1310** is displaced in a direction **x 1312** by a distance **d4 1500**, the distance curved surface **1404** extends in a direction **x 1312**. Therefore, as a result of the first and second stages, frame **1310** is displaced a total distance of distance **d3 1402** plus distance **d4 1500** in a direction **x 1312** from its position in the inactive state.

Alternatively, any type of flexure or other connection as described above can be used for connecting electrode beam **1306** to frame **1310**. Simulation results of a two-stage actuator employing one-fold flexures with each of distances **d3 1402** and **d4 1500** set to 50 micrometers and an applied voltage of 140 volts produced a frame displacement of 85.5 micrometers.

Several different frame structures and actuator configurations can be implemented. Referring to FIG. 16, a schematic view of another embodiment of a MEMS device according to this invention and generally designated **1600** is illustrated for moving a shutter **1602** in a linear direction **x 1604** in a plane parallel to the plane of a substrate surface **1606**. MEMS device **1600** includes bi-directional actuators generally designated **1608**, **1610**, **1612**, and **1614** for moving frame and attached shutter **1602** in a direction **x 1604** and opposite direction **x 1604**. Actuators **1608**, **1610**, **1612**, and **1614** are attached to frame **1616** via flexures **1616**, **1618**, **1620**, and **1622**, respectively. Actuators **1608**, **1610**, **1612**, and **1614** are connected to substrate surface **1606** via anchors **1624**, **1626**, **1628**, and **1630**, respectively.

Frame **1616** is considered a “framed” structure which surrounds actuators **1608**, **1610**, **1612**, and **1614**. Frame **1616** consists of arms **1632**, **1634**, **1636**, and **1638** for providing attachment to actuators **1608**, **1610**, **1612**, and **1614** and

shutter **1602**. Arm **1632** attaches frame **1616** to actuators **1610** and **1612**. Arm **1634** attaches frame **1616** to actuators **1608** and **1614**. Arms **1636** and **1638** connects arm **1632** to arm **1634**. Additionally, arm **1638** is attached to shutter **1602**.

Optical MEMS devices employing bi-directional actuators can be closely placed together for economizing substrate surface space. Referring to FIG. 17, a schematic view of a set of light pathways **1700**, **1702**, **1704**, **1706**, **1708**, **1710**, **1712**, and **1714** extending perpendicular to the substrate and a set of bi-directional actuators generally designated **1716**, **1718**, **1720**, **1722**, **1724**, **1726**, **1728**, and **1730** is illustrated. Actuators **1716**, **1718**, **1720**, **1722**, **1724**, **1726**, **1728**, and **1730** include shutters **1732**, **1734**, **1736**, **1738**, **1740**, **1742**, **1744**, and **1746**, respectively, for interacting with light pathways **1702**, **1706**, **1710**, **1714**, **1700**, **1704**, and **1712**, respectively. As shown, actuators **1716**, **1718**, **1720**, and **1722** are aligned along one side of light pathways **1700**, **1702**, **1704**, **1706**, **1708**, **1710**, **1712**, and **1714** in an opposing position to actuators **1724**, **1726**, **1728**, and **1730** in order to conserve the space on surface **1748** of the substrate. Additionally, as shown, the actuators comprising each actuator **1716**, **1718**, **1720**, **1722**, **1724**, **1726**, **1728**, and **1730** are interleaved in order to conserve the space on substrate surface **1748**.

Referring to FIG. 18, a schematic view of another set of light pathways **1800**, **1802**, **1804**, **1806**, **1808**, **1810**, **1812**, and **1814** extending perpendicular to a substrate and a set of uni-directional, two-stage actuators generally designated **1816**, **1818**, **1820**, **1822**, **1824**, **1826**, **1828**, and **1830** is illustrated. Actuators **1816**, **1818**, **1820**, **1822**, **1824**, **1826**, **1828**, and **1830** include shutters **1832**, **1834**, **1836**, **1838**, **1840**, **1842**, **1844**, and **1846**, respectively, for interacting with

light pathways **1802, 1804, 1806, 1808, 1810, 1812**, and **1814**, respectively. As shown, actuators **1816, 1820, 1822, 1824**, and **1828** are aligned along one side of light pathways **1802, 1804, 1806, 1808, 1810, 1812**, and **1814** in an opposing position to actuators **1818, 1822, 1826**, and **1830** in order to conserve the space on surface **1848** of the substrate. Additionally, as shown, the actuators comprising each actuator **1816, 1818, 1820, 1822, 1824, 1826, 1828**, and **1830** are interleaved in order to conserve the space on substrate surface **1848**.

Referring to FIG. 19, a schematic view of another set of light pathways **1900, 1902, 1904, 1906**, and **1908** extending perpendicular to a substrate and a set of framed, bi-directional actuators generally designated **1910, 1912, 1914, 1916**, and **1918** is illustated. Actuators **1910, 1912, 1914, 1916**, and **1918** include shutters **1920, 1922, 1924, 1926**, and **1928**, respectively, for interacting with light pathways **1900, 1902, 1904, 1906**, and **1908**, respectively. As shown, actuators **1910** and **1912** are aligned along one side of light pathways **1900, 1902, 1904, 1906**, and **1908** in an opposing position to actuators **1914, 1916**, and **1918** in order to conserve the space on surface **1930** of the substrate.

Although the present invention has been described with respect to the use of MEMS device for moving shutters in a linear direction along the plane of a substrate surface, the principles of the present invention also can be used for many other applications requiring actuation. Furthermore, it will be understood that various details of the invention can be changed without departing from the scope of the invention. The foregoing description is for the purpose of illustration only, and not for the purpose of limitation – the invention being defined by the claims.